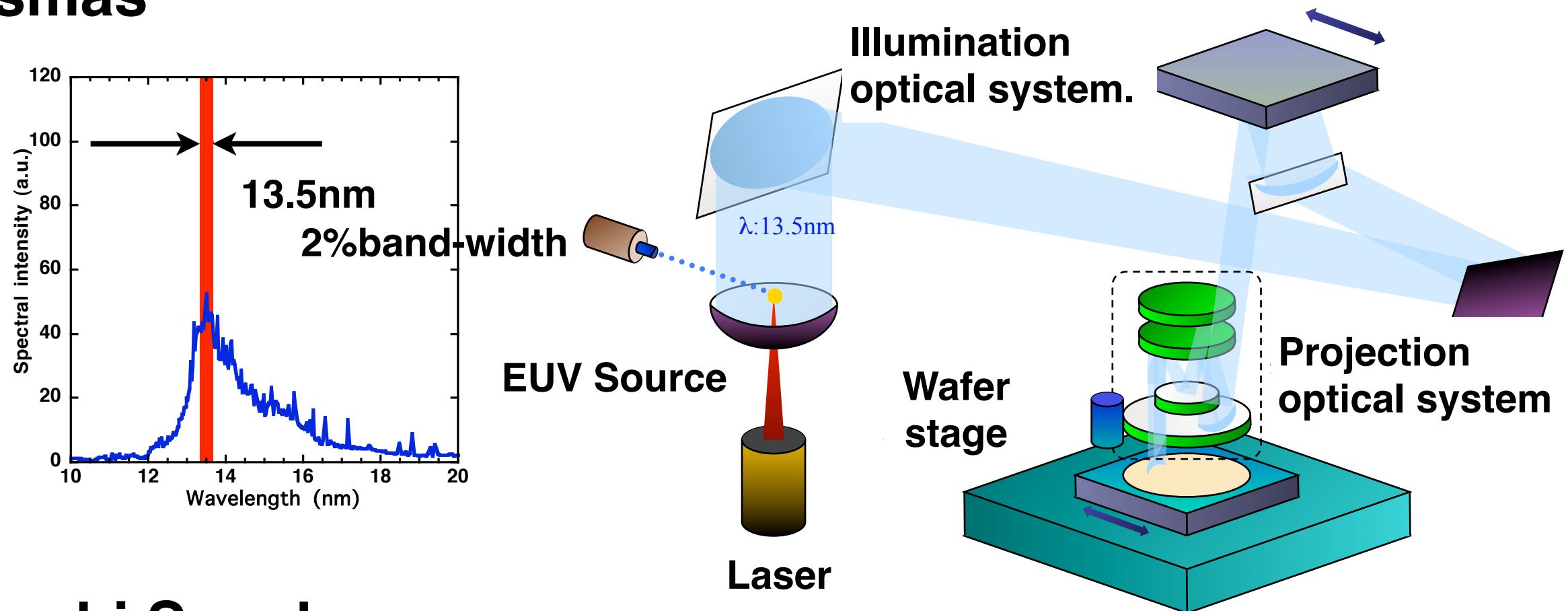


Two Dimensional Radiation Hydrodynamic Simulation for Extreme Ultra Violet Emission From Laser-produced Tin Plasmas



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- F. Koike (Kitasato University, Kanagawa, Japan) GRASP
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- K. Nishikawa (Okayama University, Japan) Average Atom Model(CRE, LTE)
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- H. Tanuma (Tokyo Metropolitan University, Japan) Experiment CXS
- T. Kato (NIFS, Toki, Japan)
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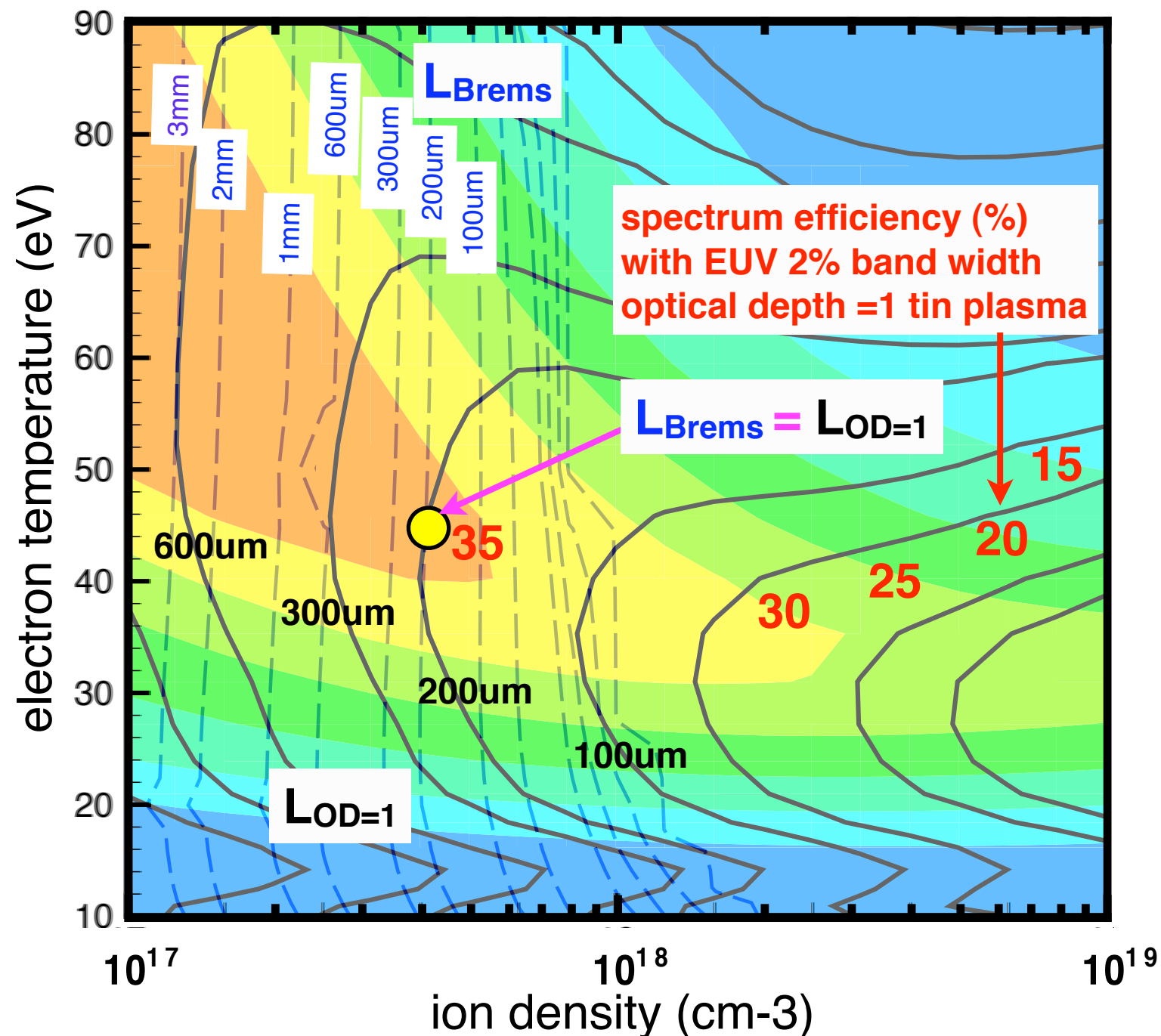
•Leading Project (MEXT)、 EUVA

Summary

We have developed 1D - and 2D- radiation hydrodynamic codes and investigated EUV emission from laser-produced tin plasma

- **X-ray spectrum and the EUV conversion efficiencies (CE) were reproduced by radiation hydrodynamic simulation using the atomic table given by Hullac.**
- **Higher EUV CE (6-8%, twice of the world record) by the CO₂ laser irradiation on tin plasma with the proper scale is predicted.**
- **Three important factors such as [laser absorption fraction], [x-ray conversion efficiency], and [spectral efficiency] should be optimized to get high EUV CE.**
- **Double pulse effect disappears with pulse duration of 40ns, and CE is decreased into that with single CO₂ irradiation on tin target.**

Low density region with ion density $\sim 10^{17}$ gives higher fraction of EUV power compared to total x-ray.

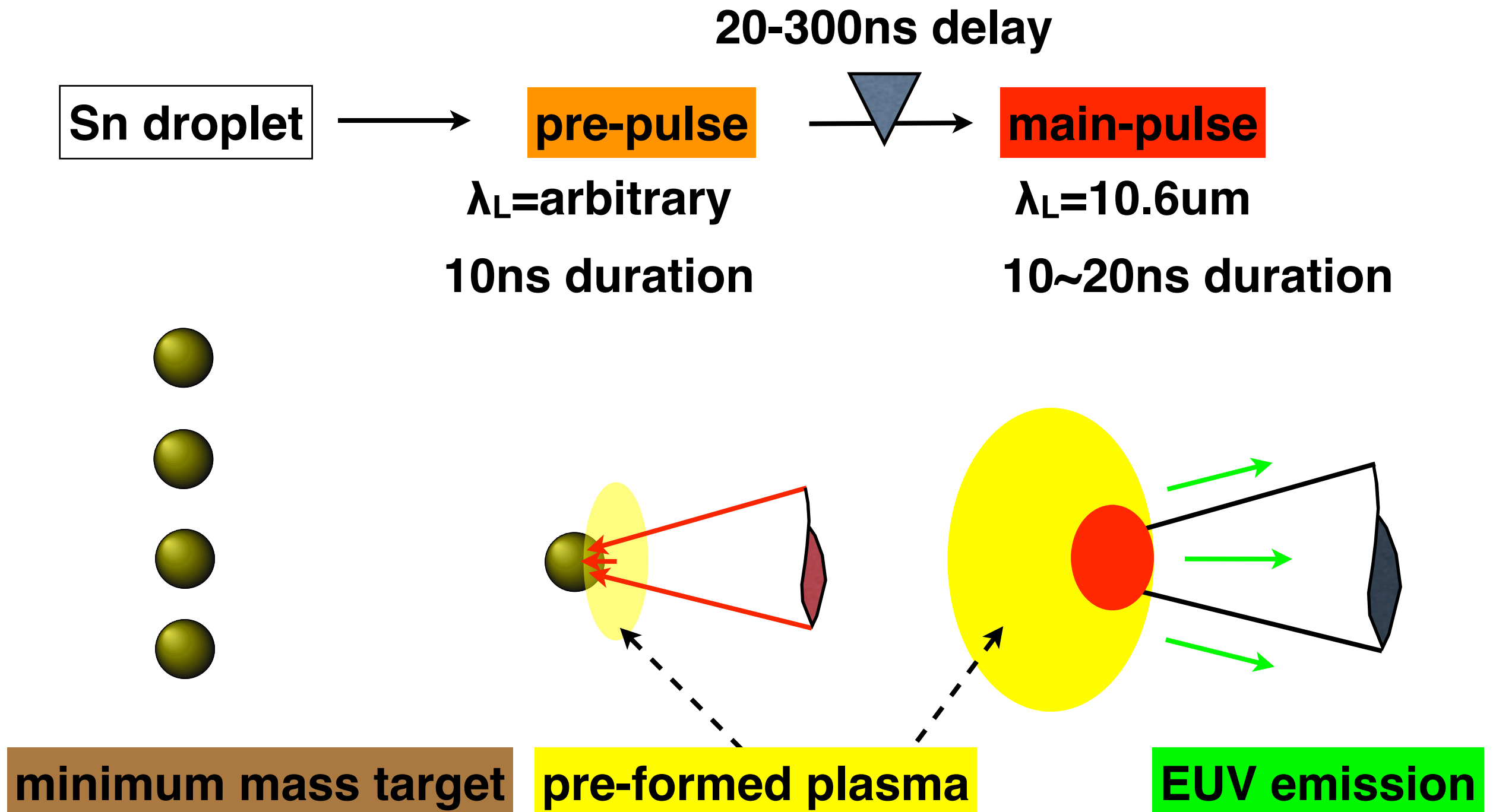


In order to obtain the higher EUV CE, we should achieve three conditions.

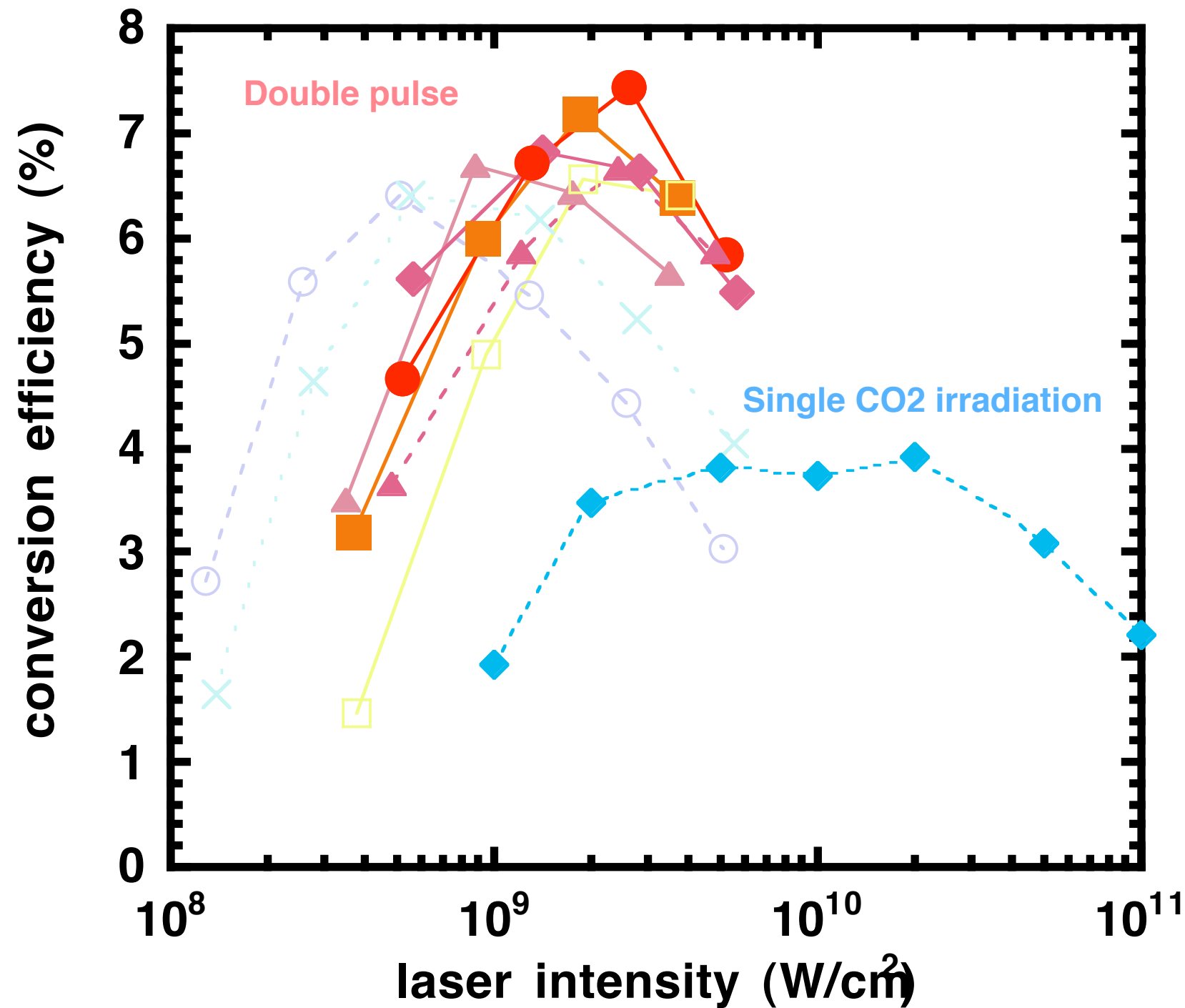
- 1) High EUV spectral efficiency should be higher.
- 2) Plasma scale length should be larger than the laser absorption scale (CO2). $L > L_{\text{Brems}}$
- 3) Plasma scale length should be that giving the EUV optical depth (OD) =1. $L \sim L_{\text{OD}=1}$

In the density-temperature phase, the point with $n_i=4 \times 10^{17} \text{ cm}^{-3}$ and $T_e=45 \text{ eV}$, $L_{\text{Brems}}=L_{\text{OD}=1}=200 \mu\text{m}$, is estimated to be best.

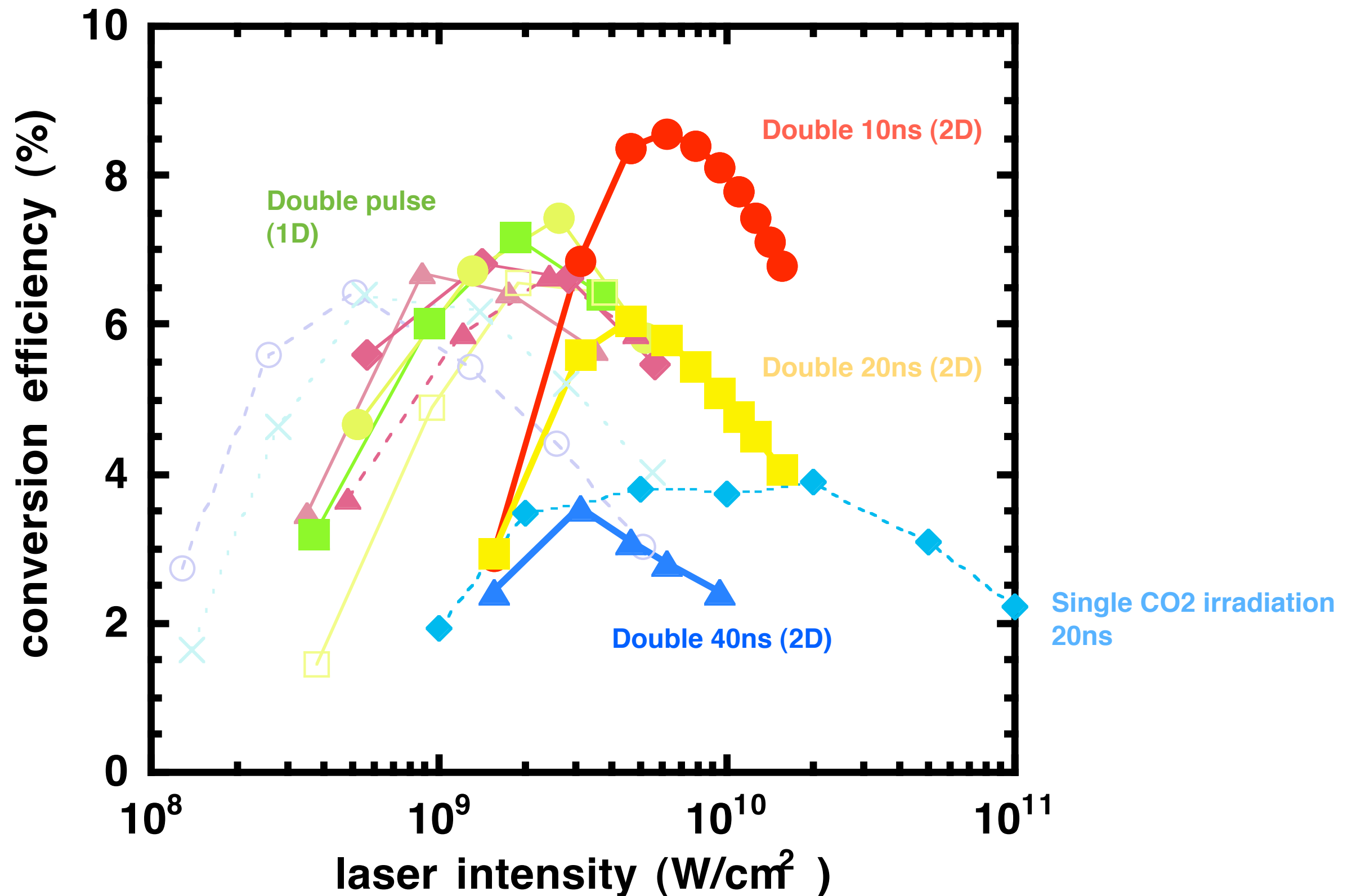
Double pulse irradiation scheme



Double pulse scheme with CO₂ main pulse can give 6-8% EUV CE which is twice of that given by single CO₂ irradiation on tin target.

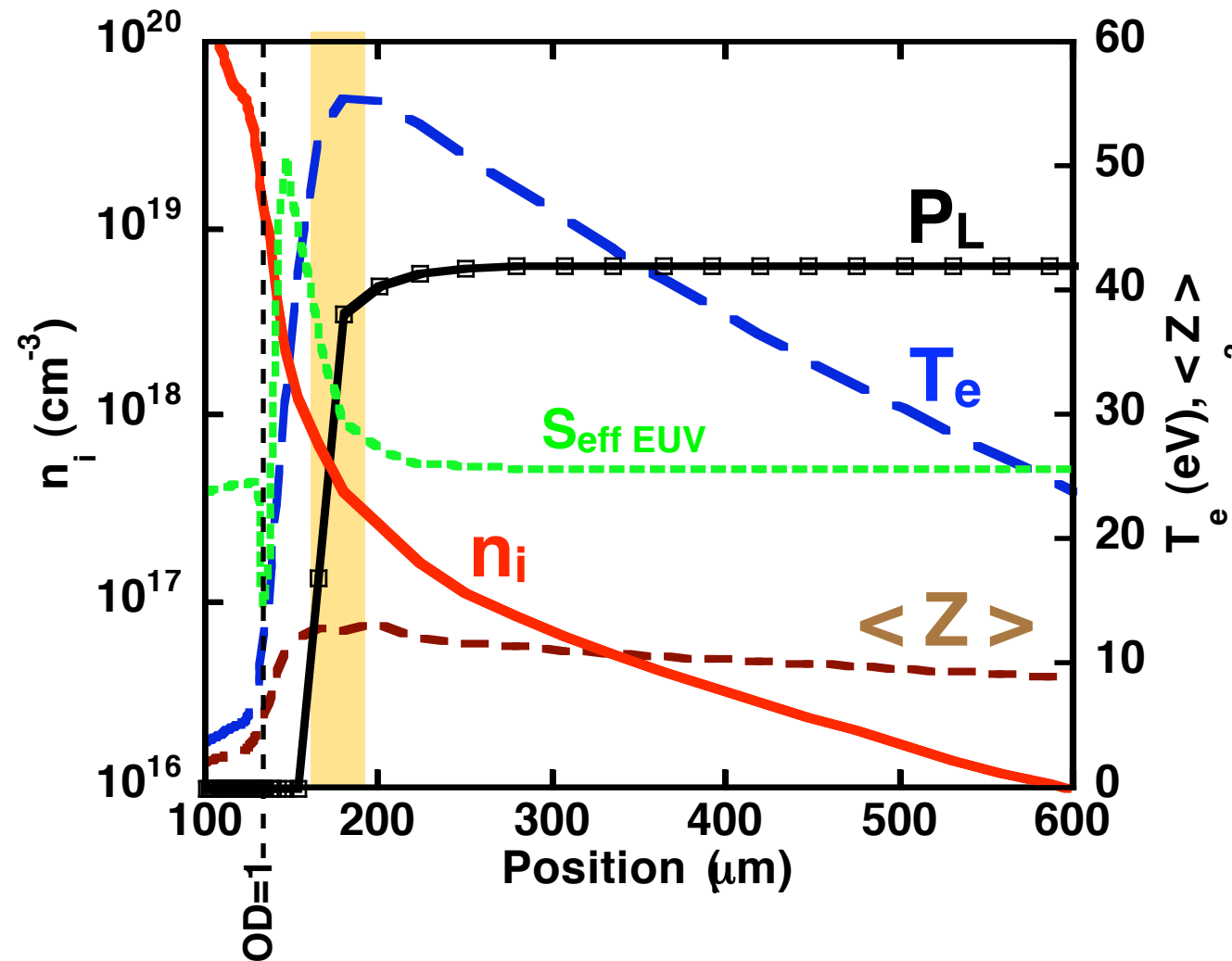


Double pulse scheme with CO₂ main pulse can give 6-8% EUV CE which is twice of that given by single CO₂ irradiation on tin target.

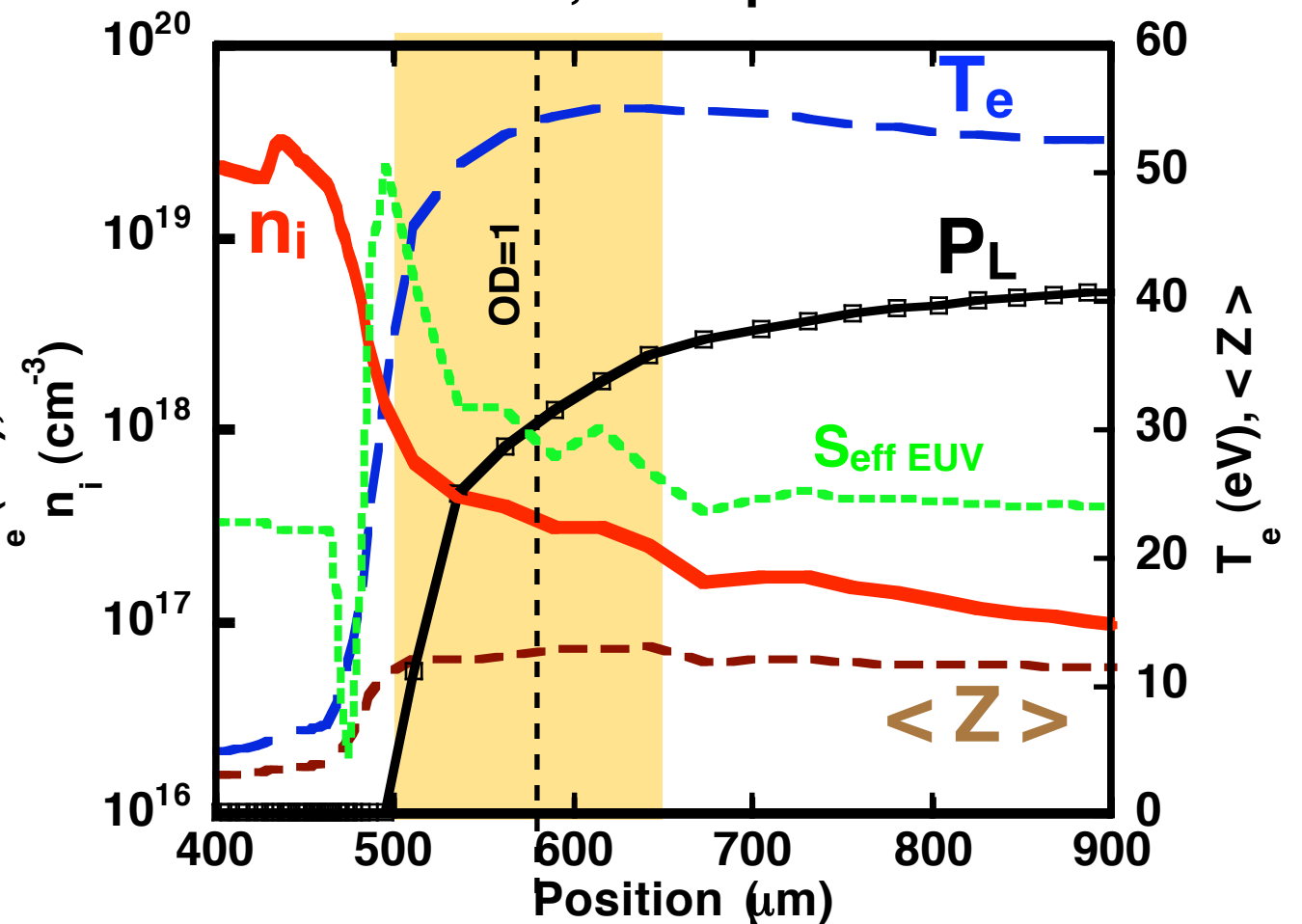


Double pulse irradiation gives higher EUV conversion efficiency.

Single CO2 laser irradiation
 $2 \times 10^{11} \text{ W/cm}^2$, 20ns pulse



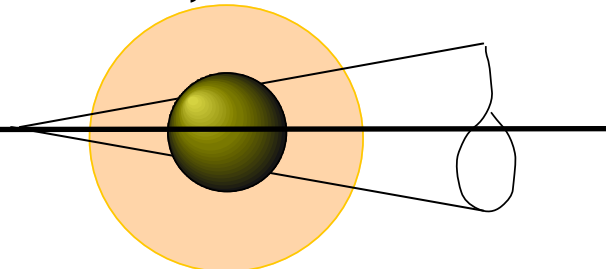
Double pulse irradiation
 prepulse(2w)+CO2 laser
 $1 \times 10^9 \text{ W/cm}^2$, 20ns pulse



Laser abs. fraction	46%
X-ray CE	48%
$P_{\text{EUV}}/P_{\text{x-ray}} \times 100$	14.9%
EUV CE	3.3%

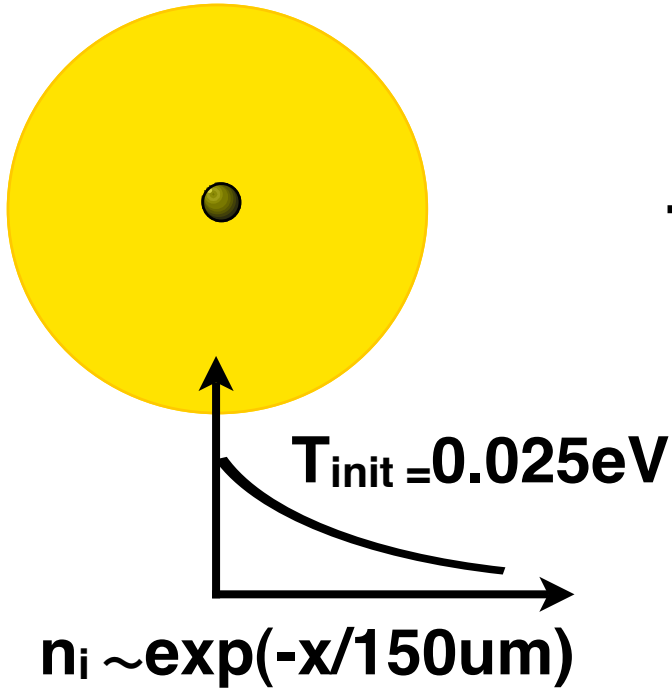
91%
69%
11.4%
7.2%

Sn 100 μm
 diameter
 $F=30, d=-0.3$

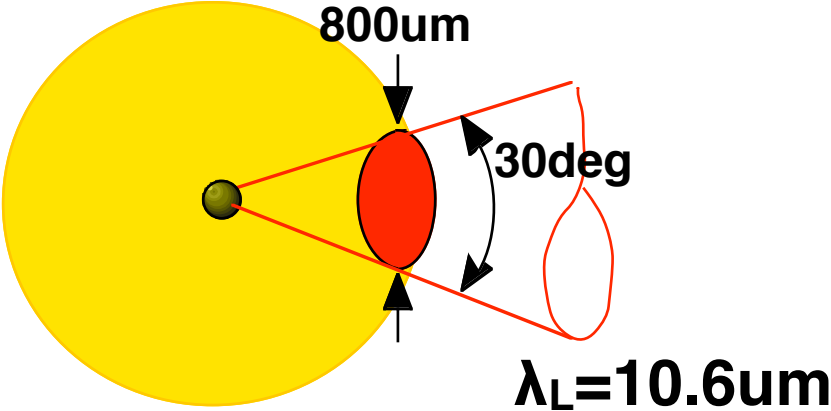


2D Simulation for Double pulse irradiation scheme

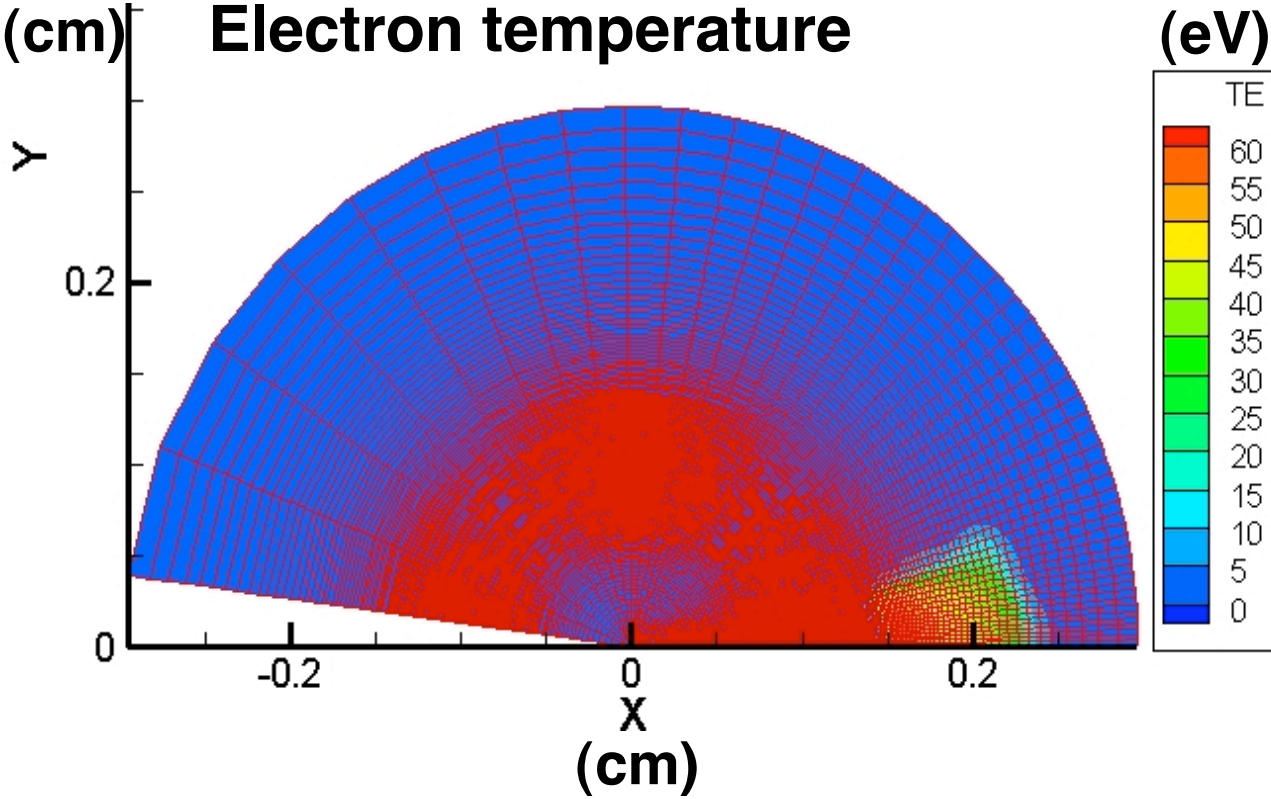
initial condition



main pulse (CO2) irradiation



For the initial condition of 2D simulation, we assume the density profile with appropriate density scale length.



2D cylindrical axis symmetry

We have developed the radiation-hydrodynamic code “Star”

Basic Equations

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{v} = 0$$

continuity equation

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho} \nabla(p + q)$$

momentum equation

$$\rho c_{vi} \frac{DT_i}{Dt} = - \left\{ T_i \left(\frac{\partial p_i}{\partial T_i} \right)_\rho + q \right\} \nabla \cdot \vec{v} + \alpha(T_e - T_i) + \nabla \cdot (\kappa_i \nabla T_i)$$

ion energy equation

$$\rho c_{ve} \frac{DT_e}{Dt} = -T_e \left(\frac{\partial p_e}{\partial T_e} \right)_\rho \nabla \cdot \vec{v} - \alpha(T_e - T_i) + \nabla \cdot (\kappa_e \nabla T_e) + S_L + S_{Rad}$$

electron energy equation

$$S_L = (k_L \cdot \nabla) \cdot I_L$$

Laser heating term

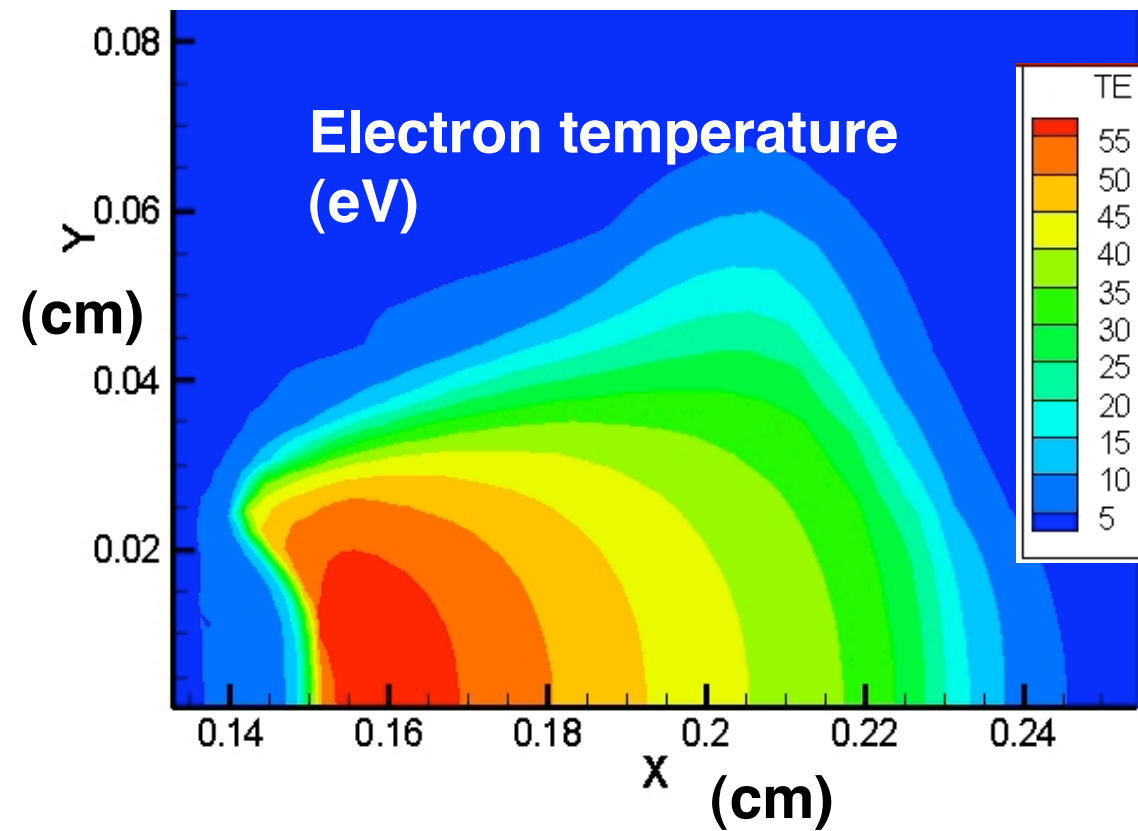
$$\rho \frac{D}{Dt} \left(\frac{E_\nu}{\rho} \right) + \nabla \cdot D_\nu \nabla E_\nu = 4\pi\eta_\nu - c\chi_\nu E_\nu$$

multi-group diffusion approximation

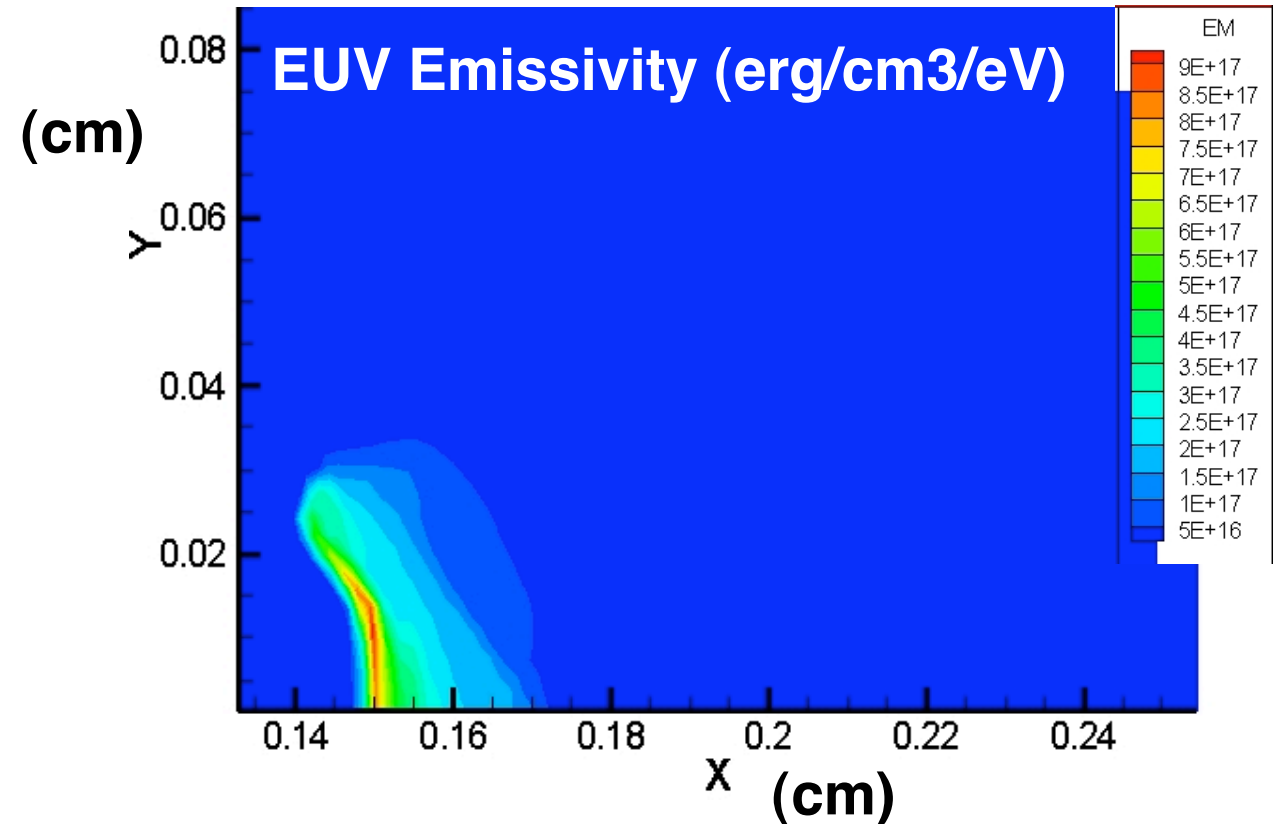
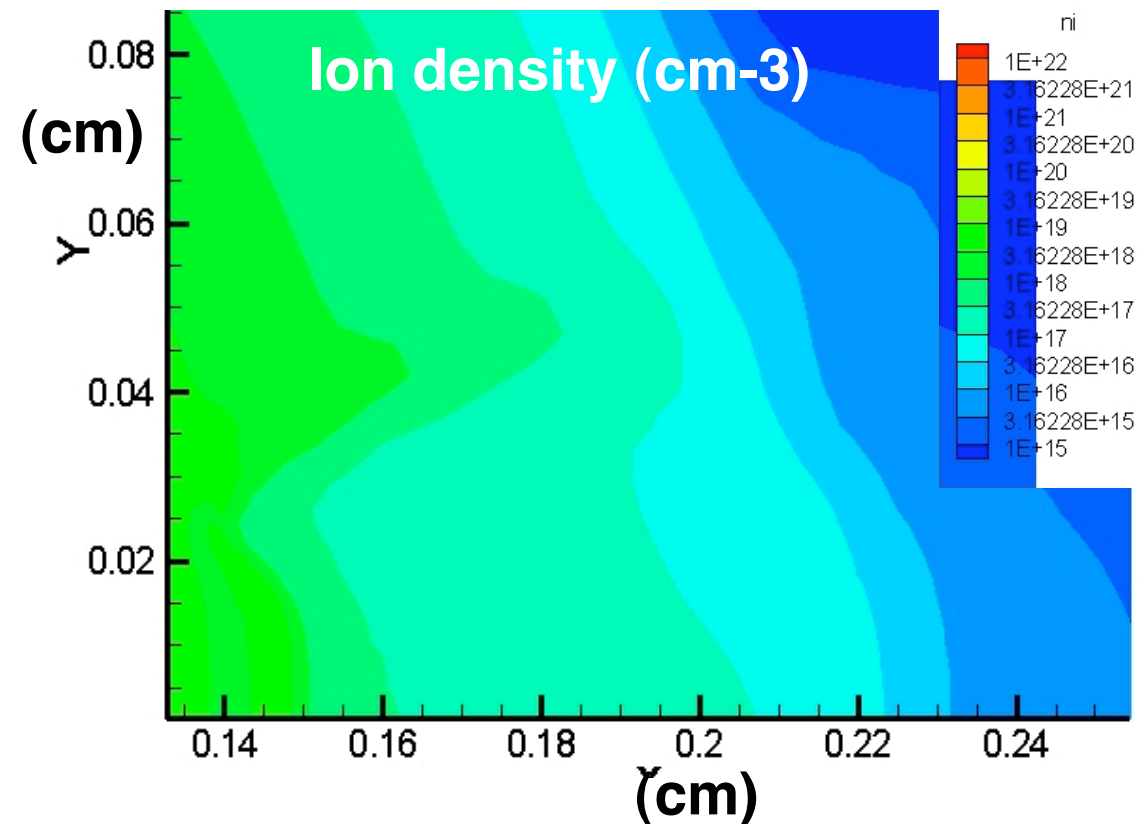
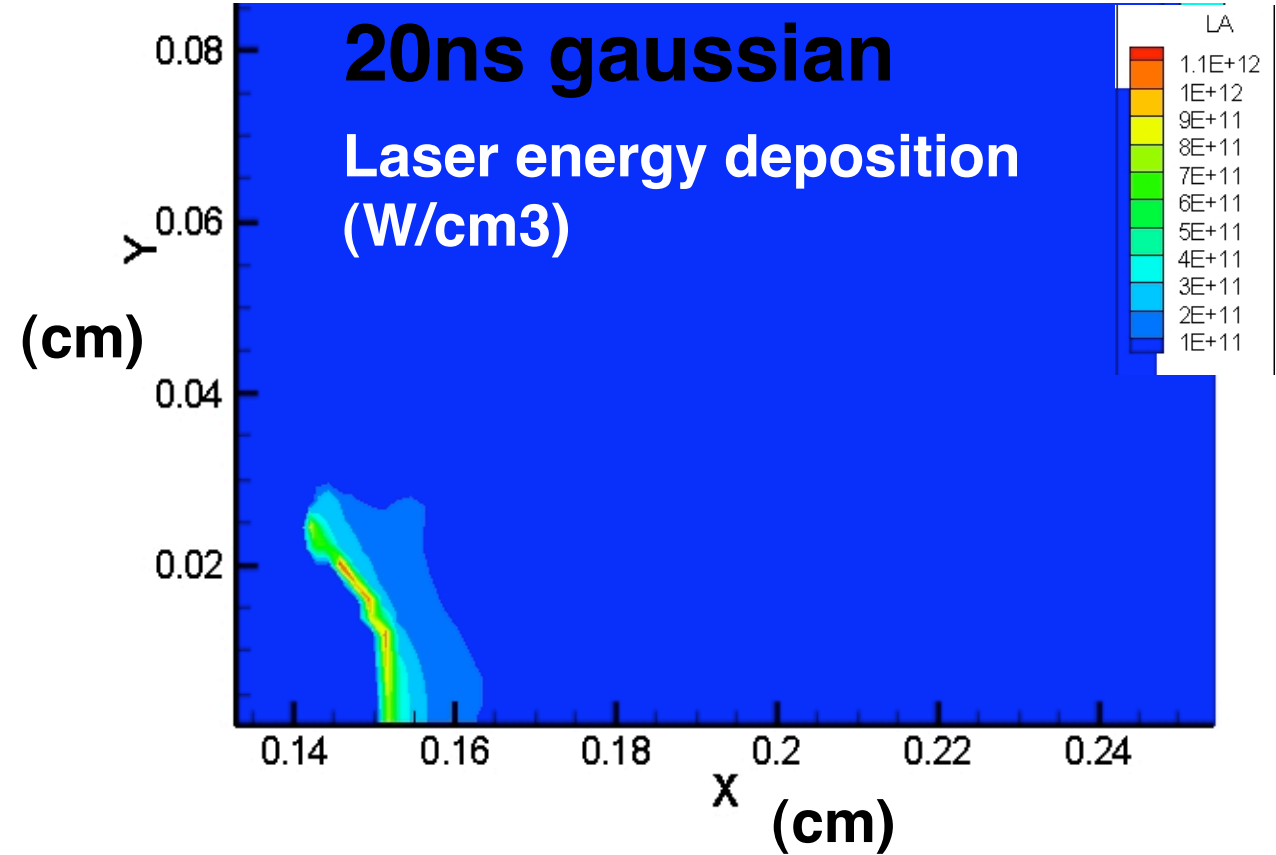
$$S_{Rad} = - \int (4\pi\eta_\nu - c\chi_\nu E_\nu) d\nu$$

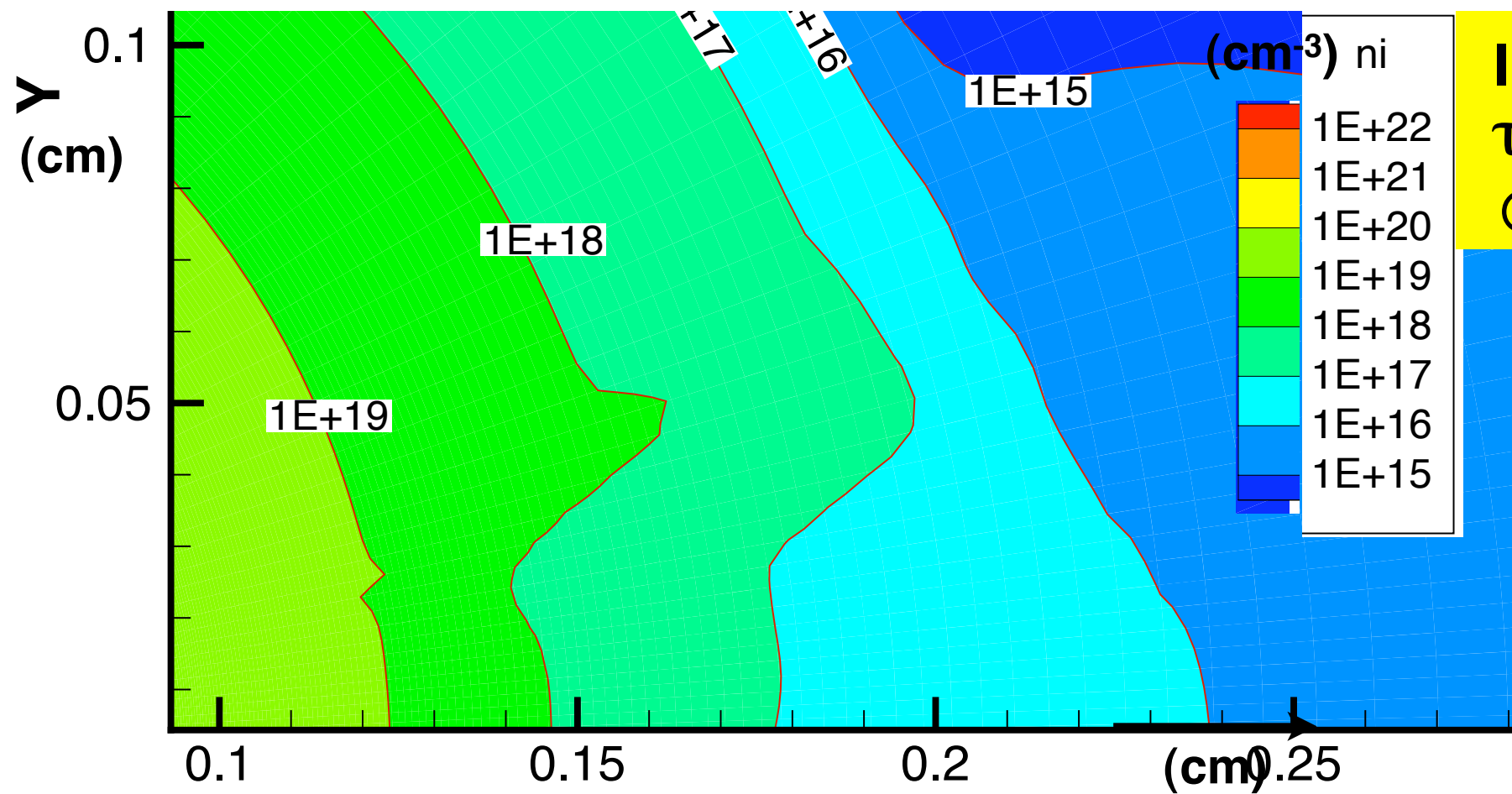
Radiation heating term

2D spherical axis symmetry @laser peak



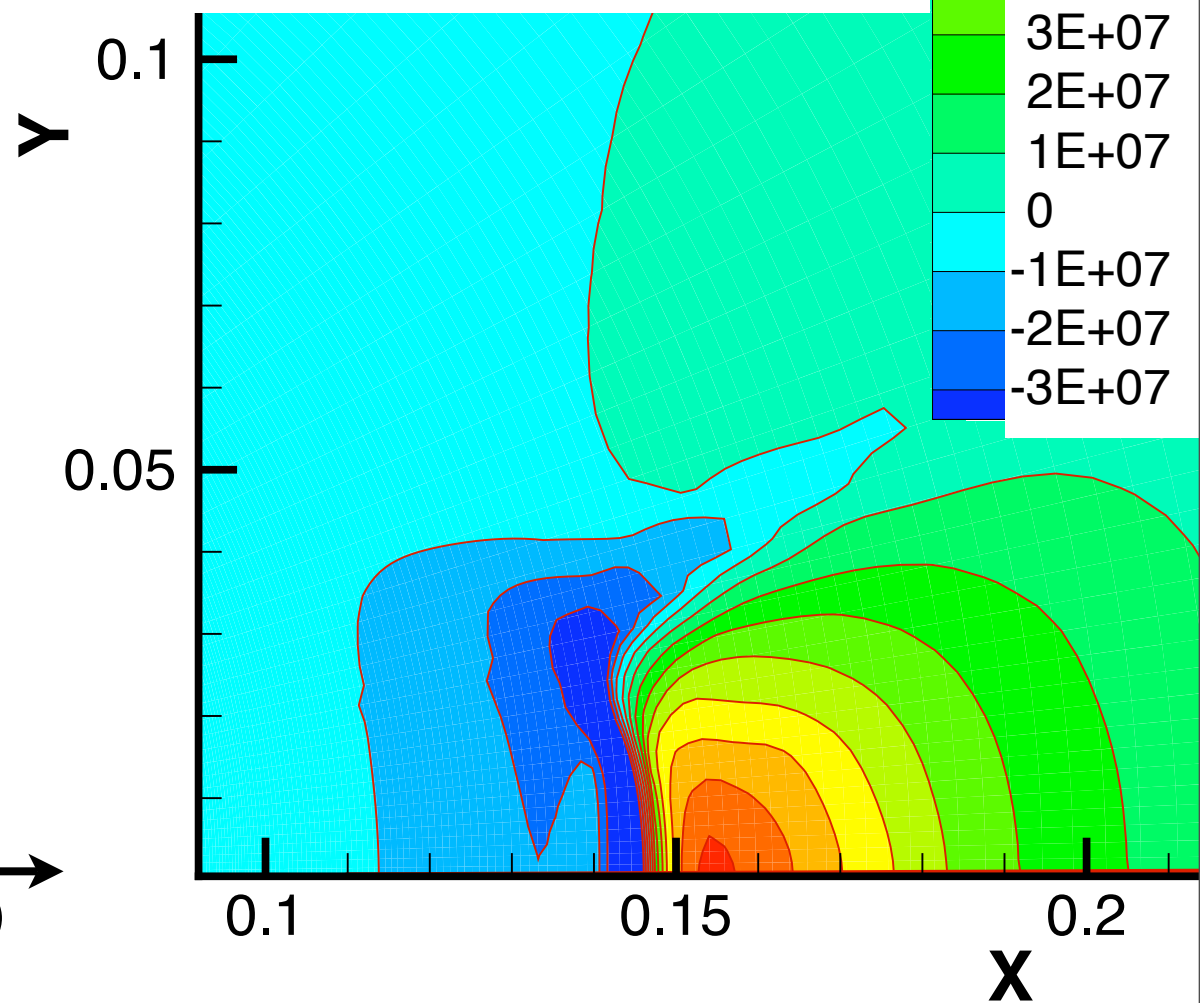
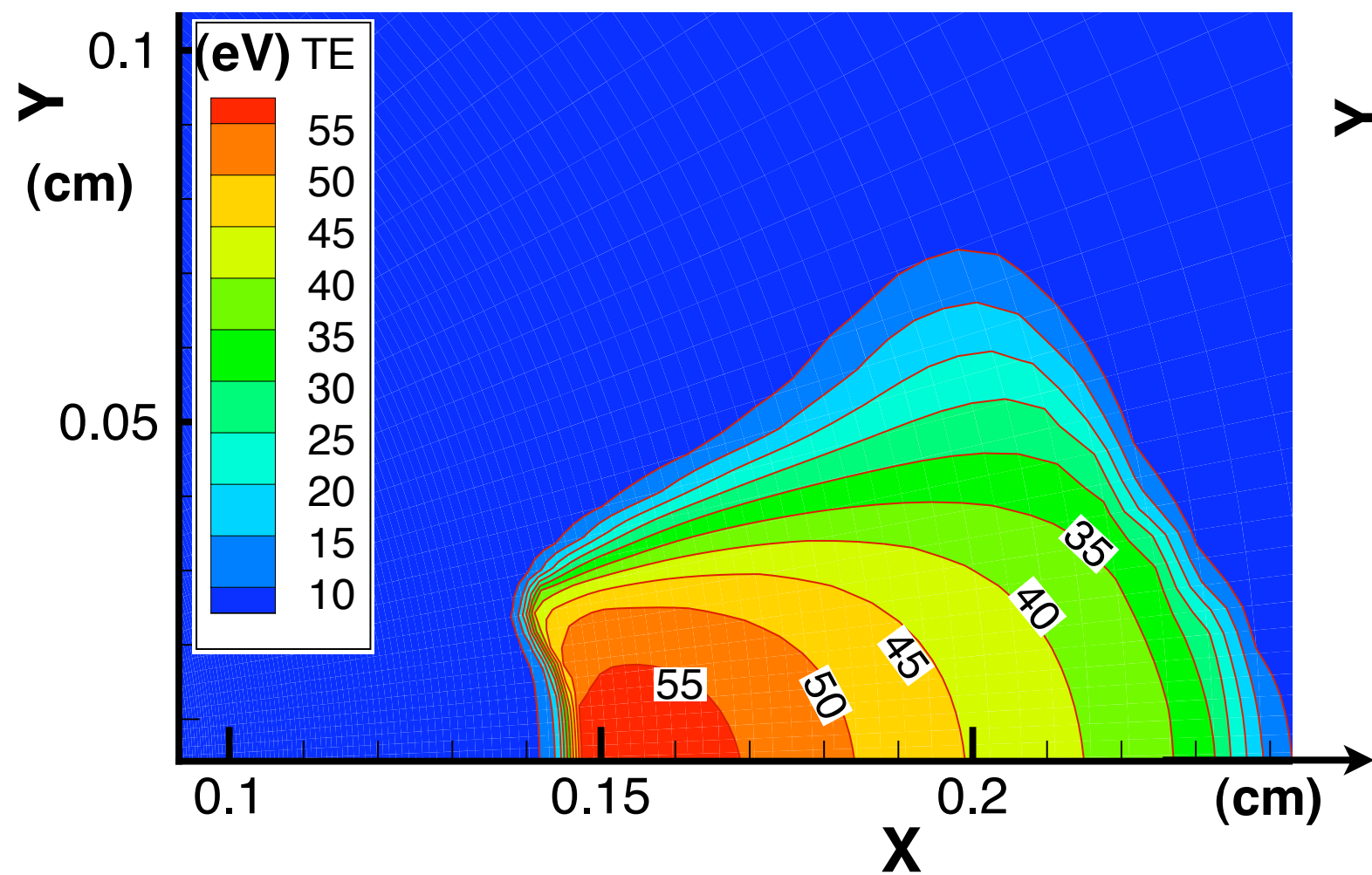
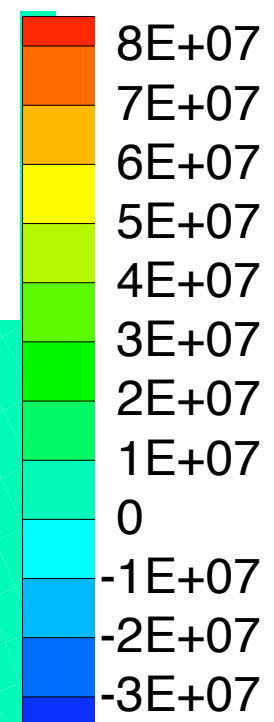
CO2 pulse intensity $5 \times 10^9 \text{ W/cm}^2$

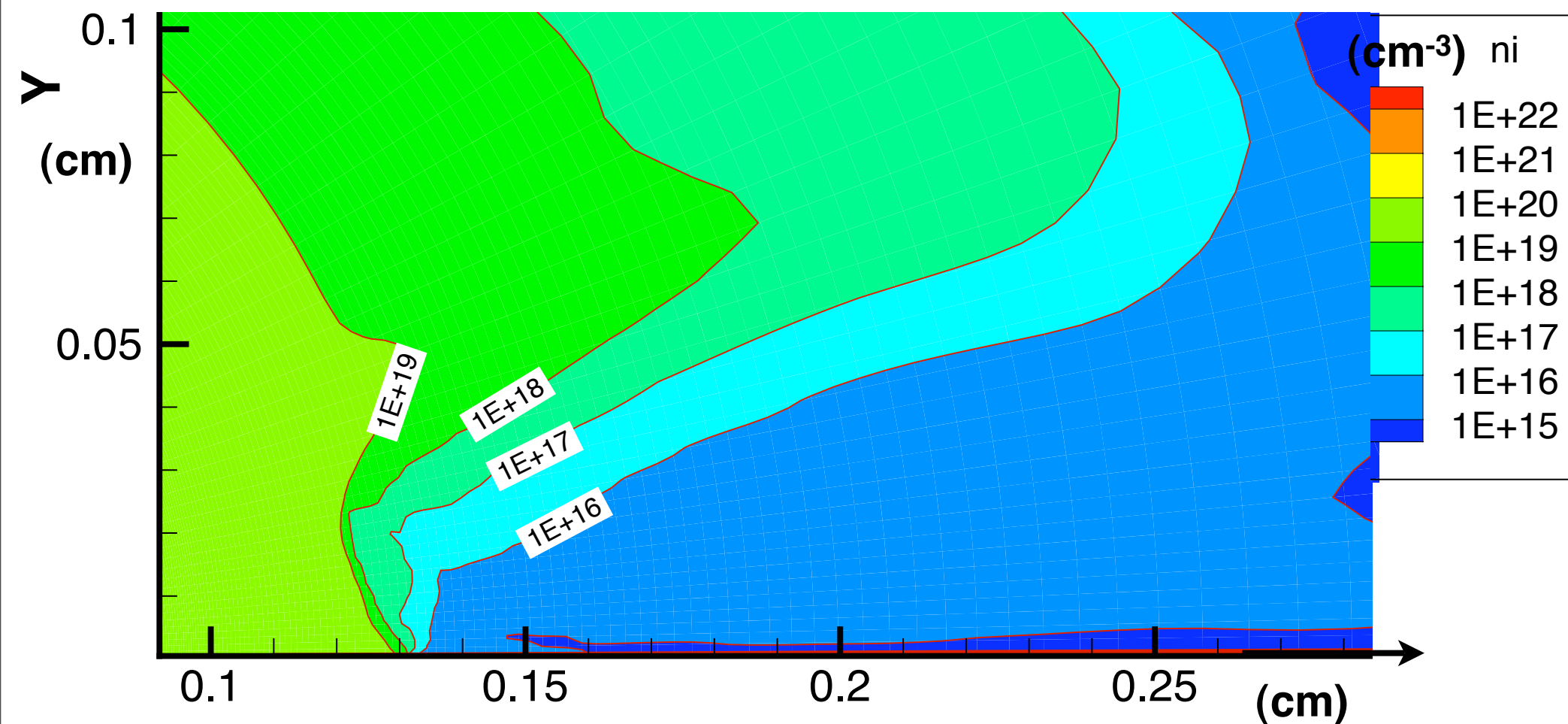




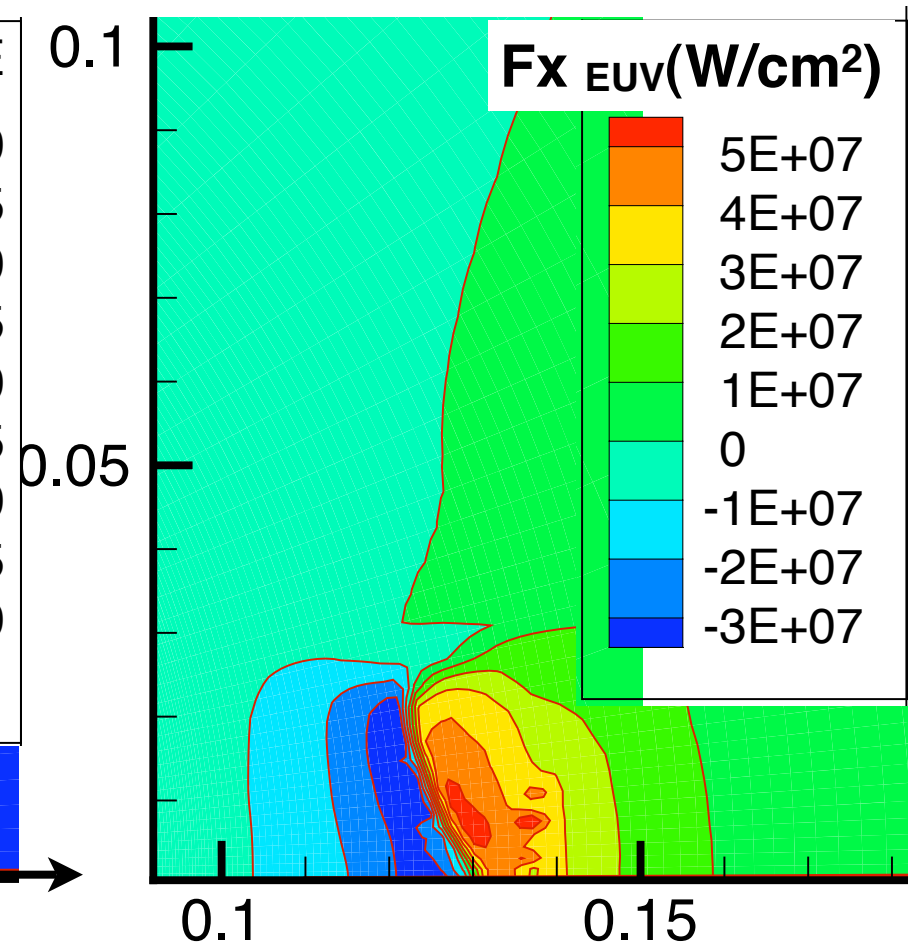
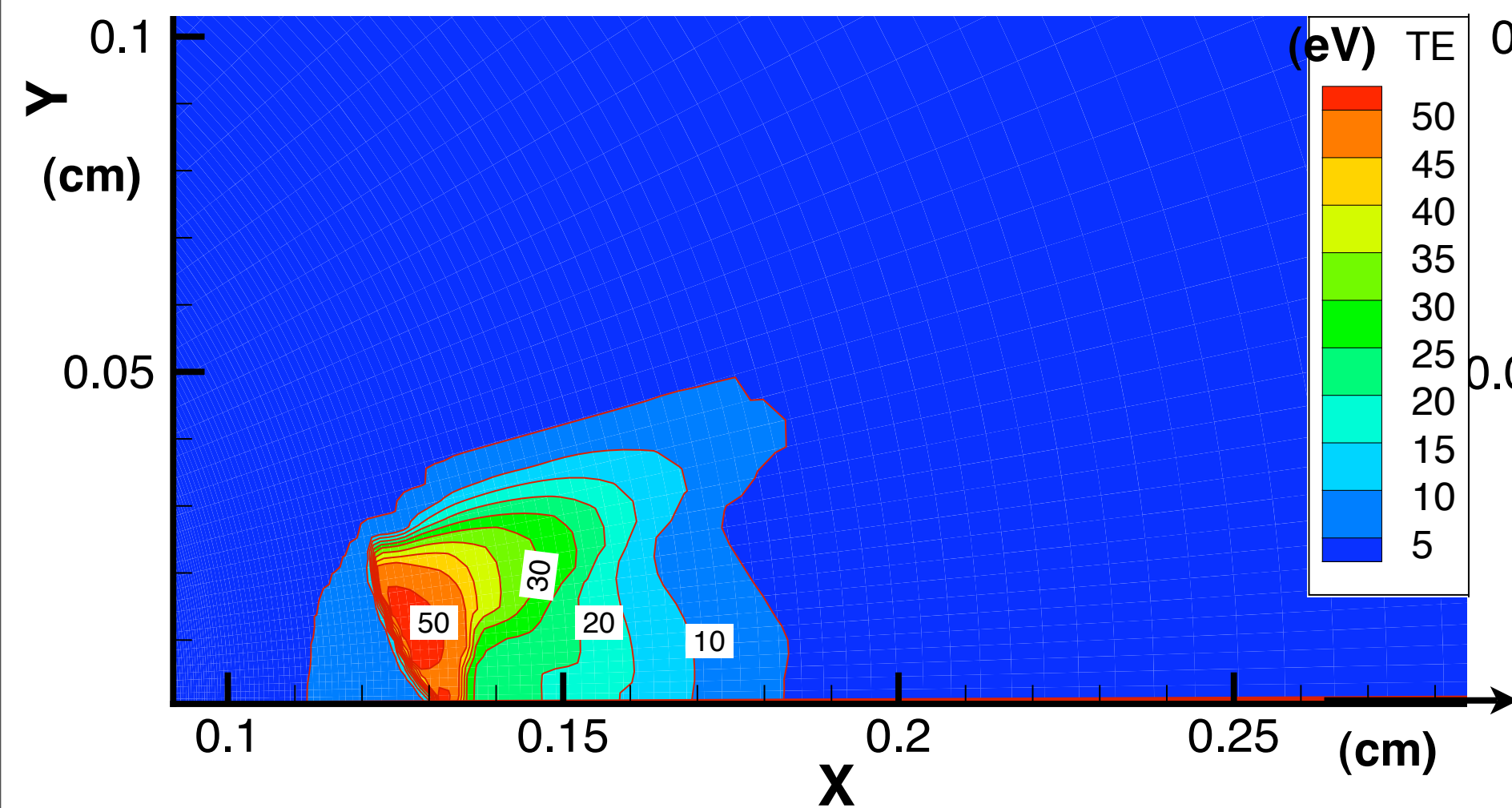
$I_L = 9.4 \times 10^9 \text{ W/cm}^2$
 $\tau_L = 10 \text{ ns}$
@laser peak

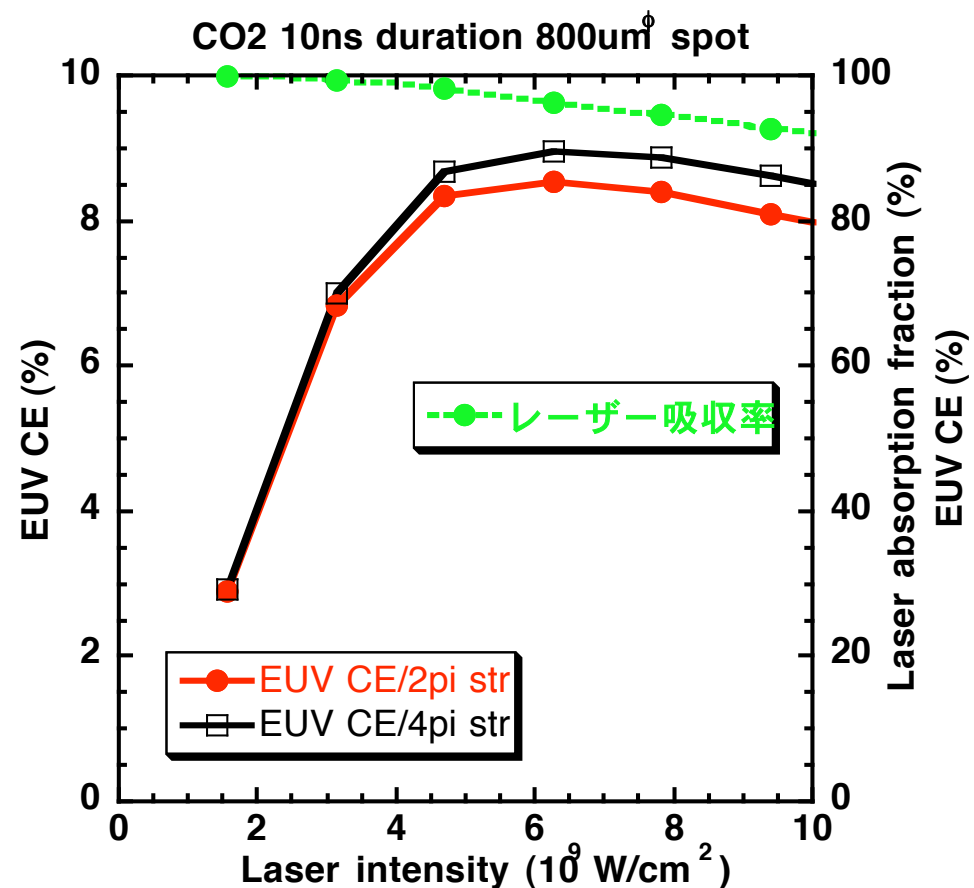
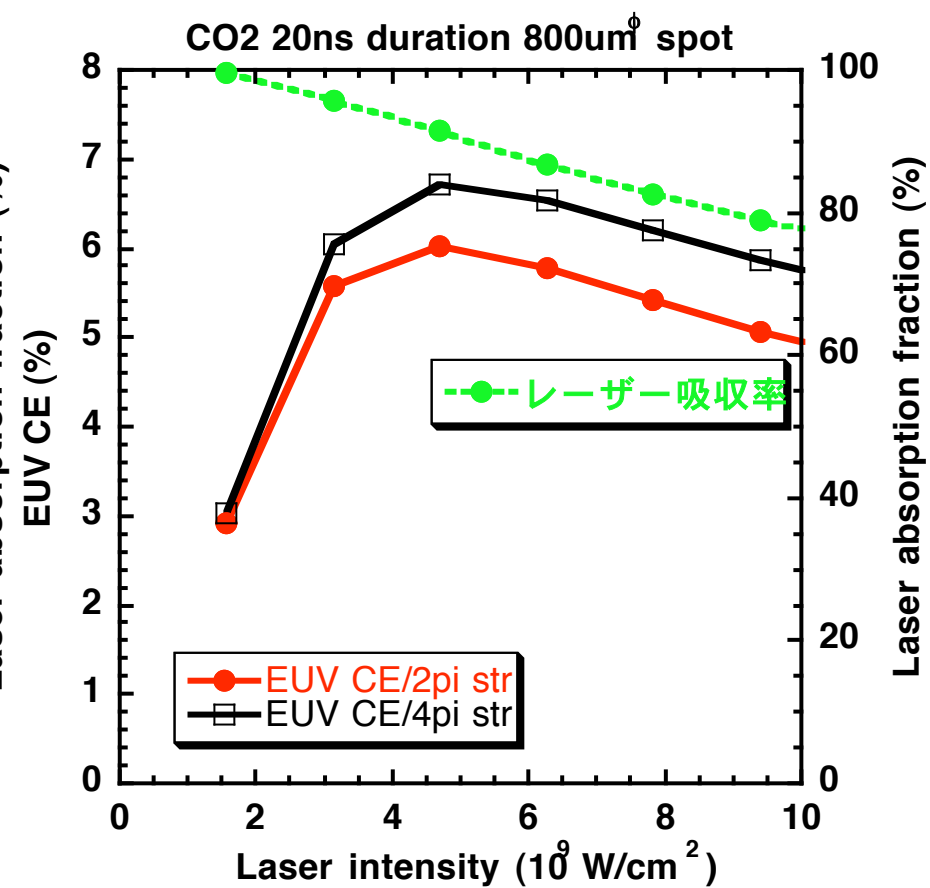
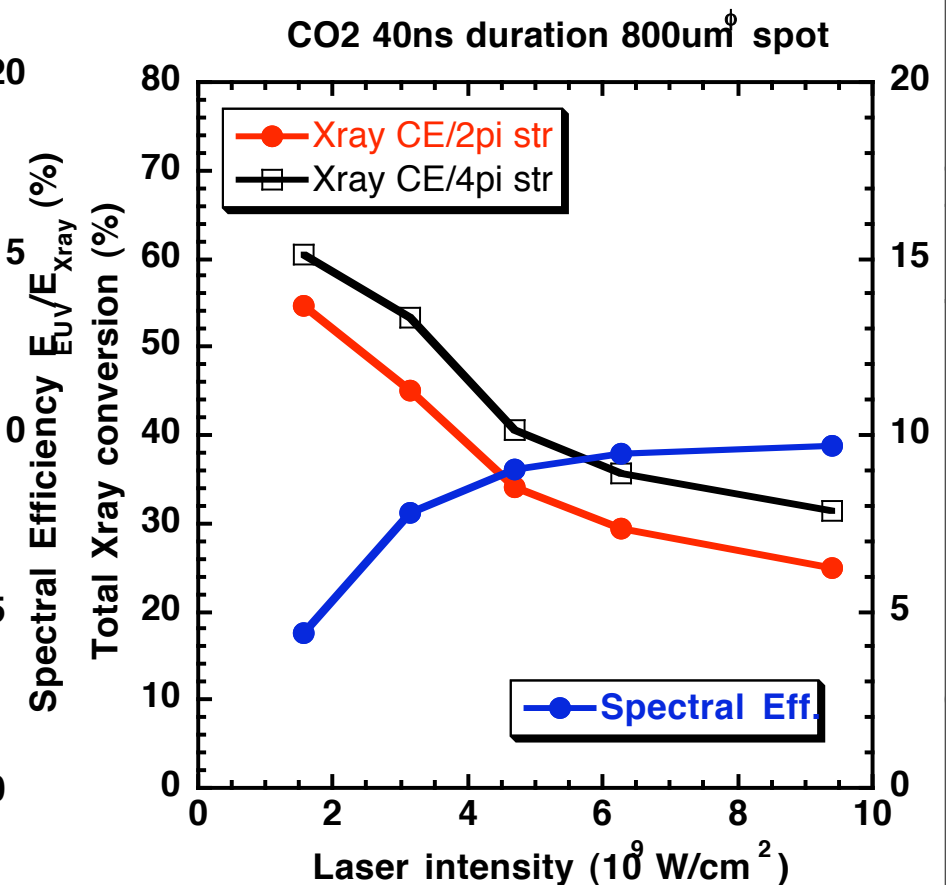
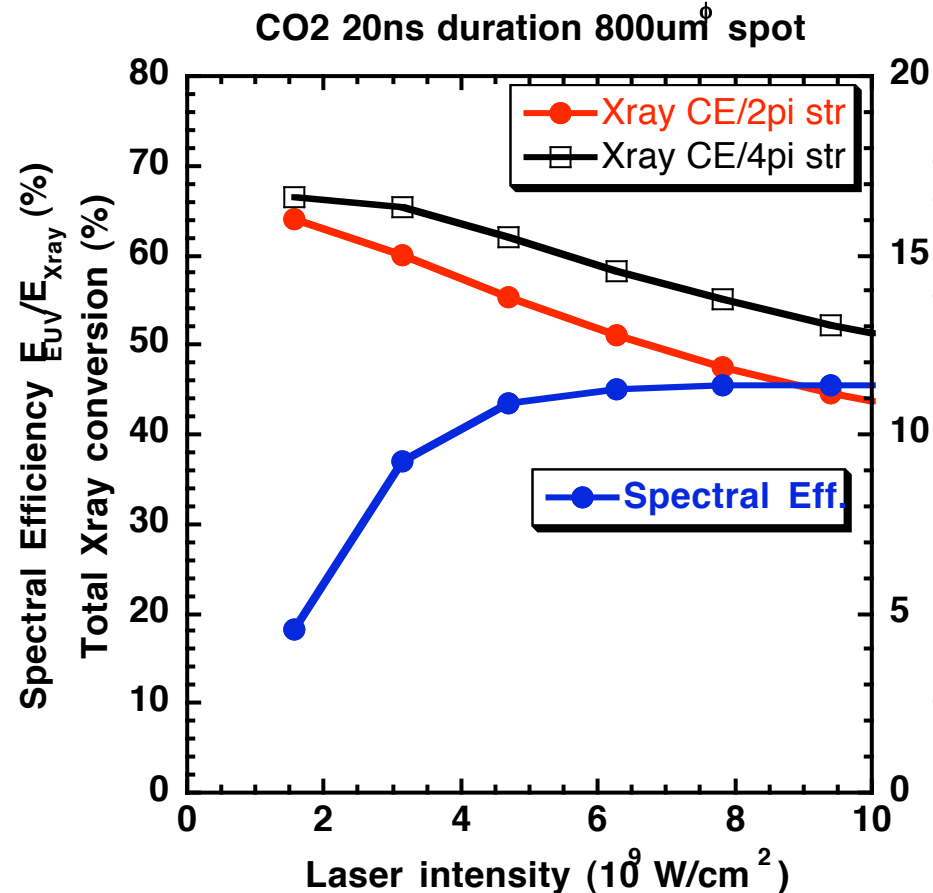
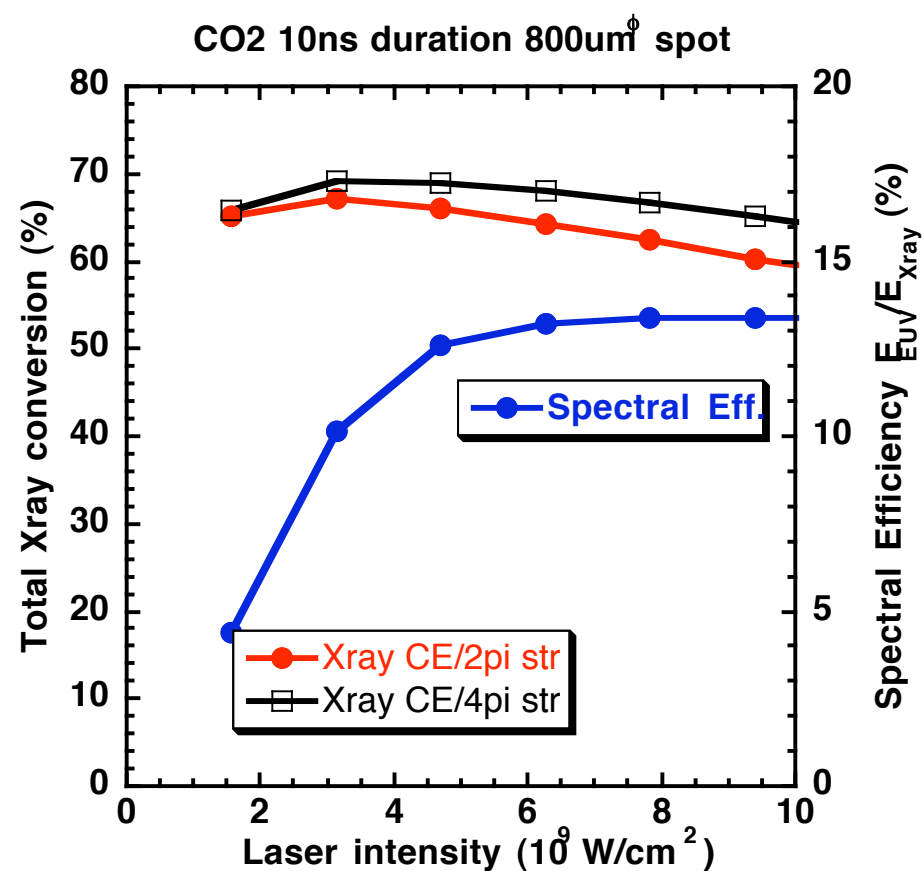
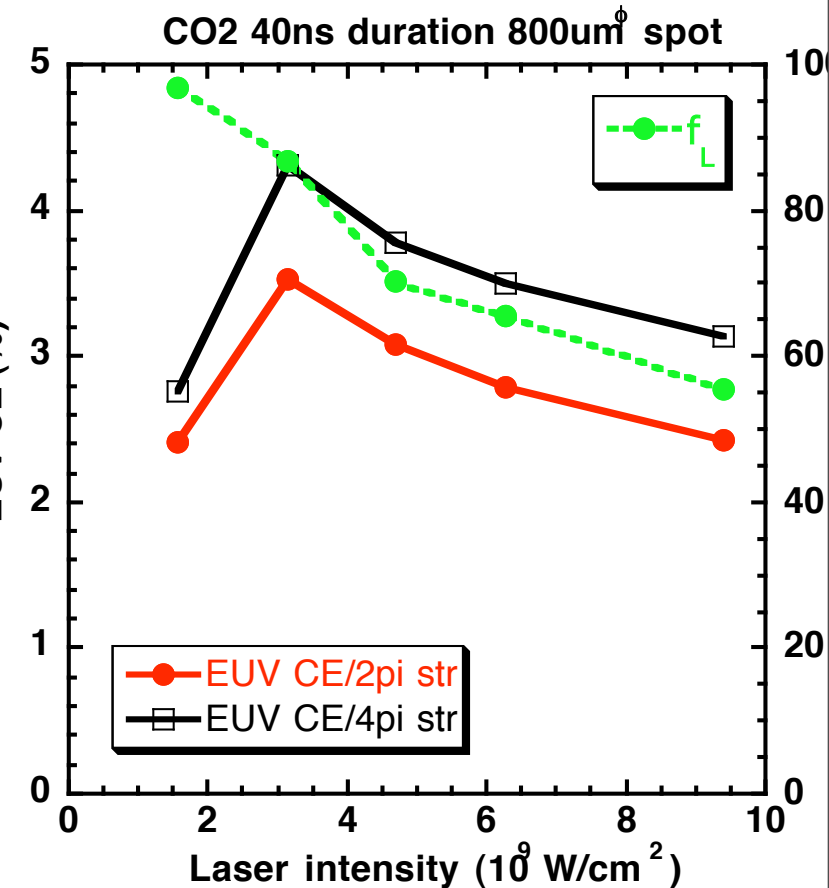
Fx EUV
(W/cm²)



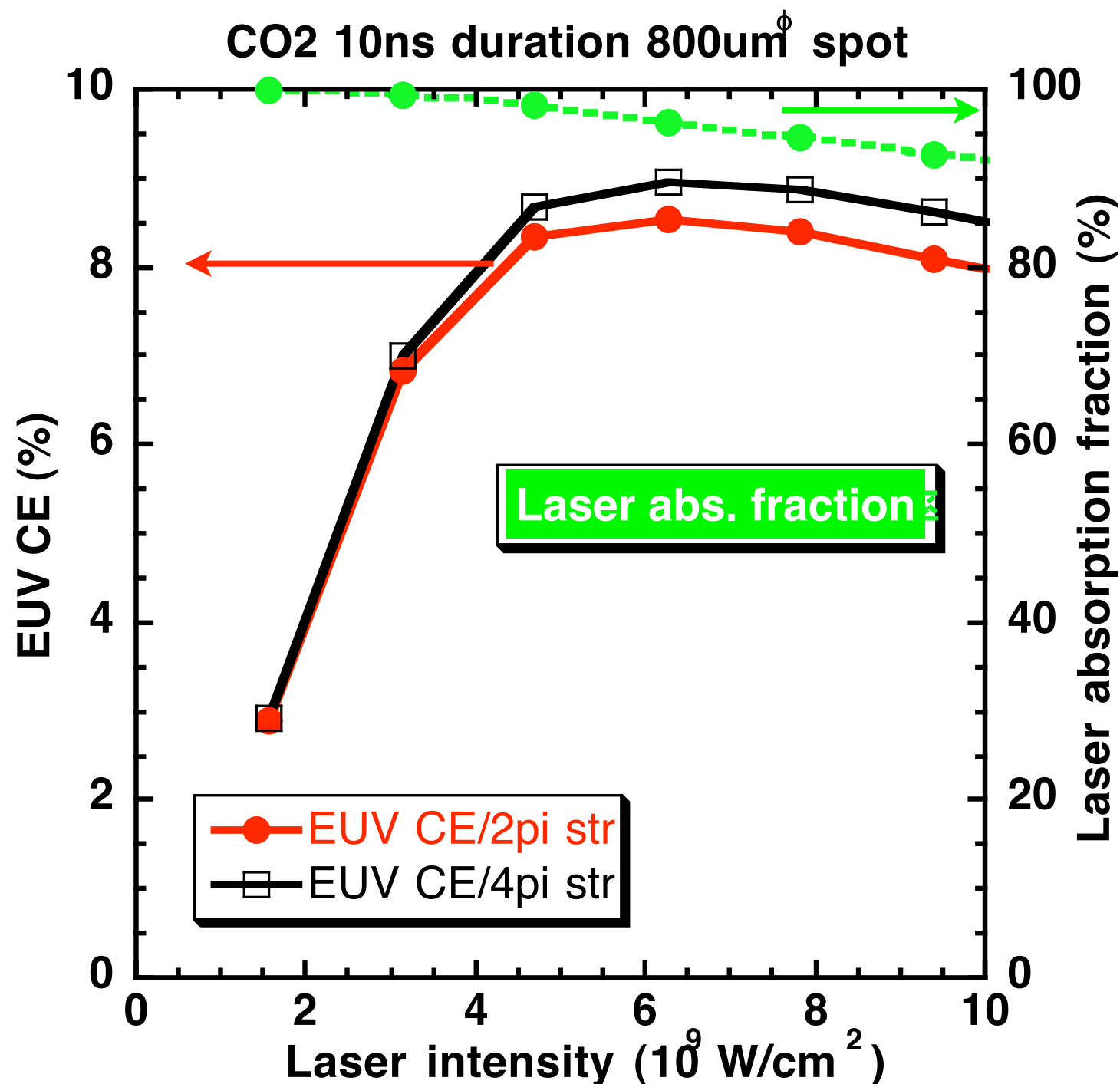


$I_L = 9.4 \times 10^9 \text{ W/cm}^2$
 $\tau_L = 40 \text{ ns}$
@laser peak



$\tau=10\text{ns}$  $\tau=20\text{ns}$  $\tau=40\text{ns}$ 

Optimization of plasma condition by 2D simulations gives more than 8% EUV CE which is roughly twice of current best data.



(EUV output estimation)

Laser intensity: $6 \times 10^9 \text{ W/cm}^2$

Pulse duration: 10ns

Laser abs. fraction: 0.9

EUV CE: 0.08

Emission area: $2.8 \times 10^{-3} \text{ cm}^2$
(600 μm ϕ)

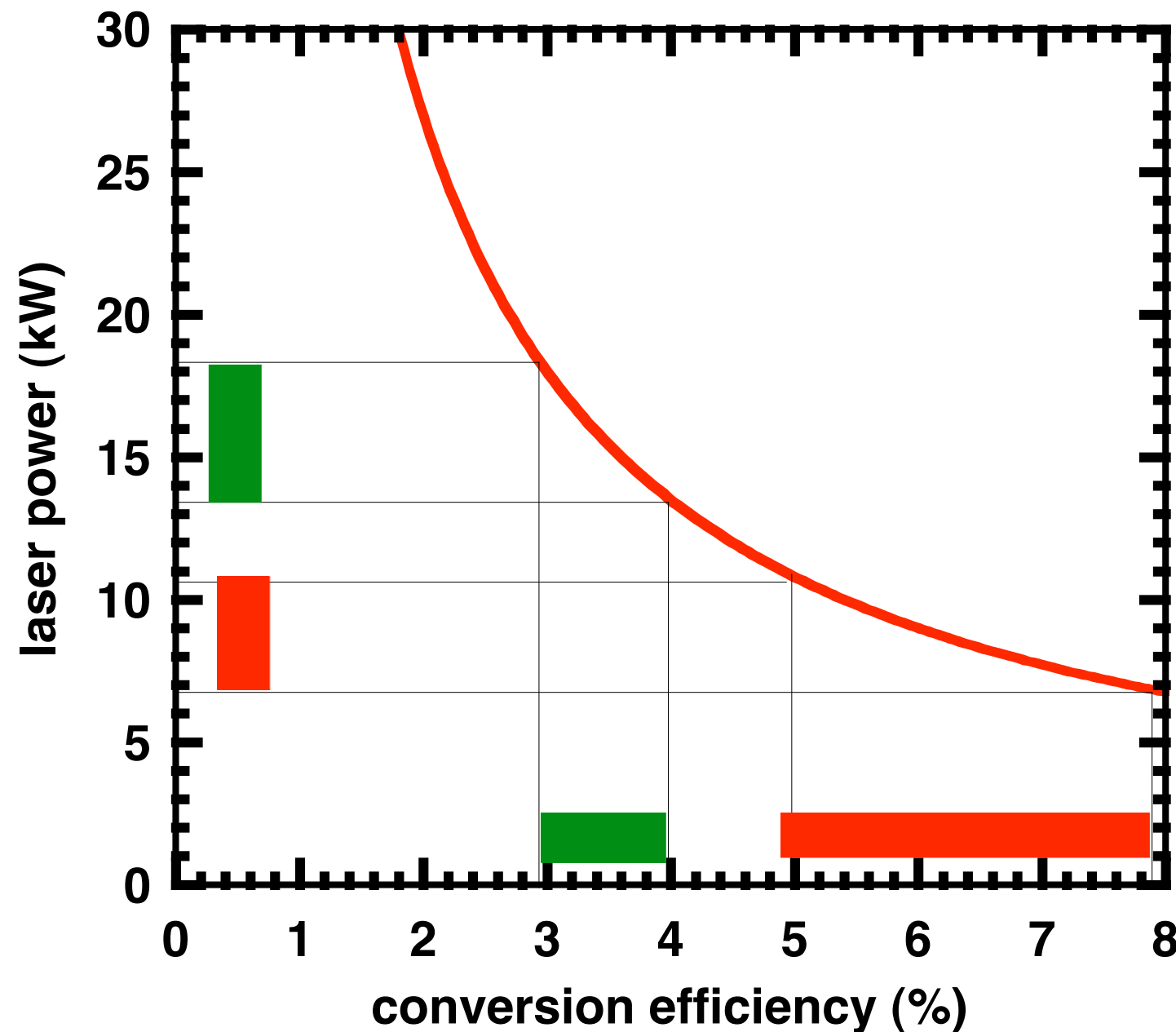
Repetition rate: $1 \times 10^5 \text{ (1/s)}$

Efficiency of
focusing system: 0.3

Final output power **363W**

Requirement :180W is fulfilled.

To get 180W output at the intermediate focus, 7-10kW laser input is required with 5-8% EUV conversion efficiency.



We can get 7-10kW
CO2 laser power
today.

+

Double pulse scheme
can give 6-8% EUV CE.



We can obtain 180W
output at the
intermediate focus.

We have developed 1D - and 2D- radiation hydrodynamic codes and investigated EUV emission from laser-produced tin plasma

- **X-ray spectrum and the EUV conversion efficiencies (CE) were reproduced by radiation hydrodynamic simulation using the atomic table given by Hullac.**
- **Higher EUV CE (6-8%, twice of the world record) by the CO₂ laser irradiation on tin plasma with the proper scale is predicted.**
- **Three important factors such as [laser absorption fraction], [x-ray conversion efficiency], and [spectral efficiency] should be optimized to get high EUV CE.**
- **Double pulse effect disappears with pulse duration of 40ns, and CE is decreased into that with single CO₂ irradiation on tin target.**
- **In future work, we will optimize the laser and target conditions in order to get higher EUV CE with including the multi-expansion effect by two-dimensional radiation hydro simulations.**